The Consummate Engineer

Real Schematics (Part 1)

Passives and Parasitics

You already know that each issue of *Circuit Cellar* has several circuit schematics complete with lots of resistors, capacitors, inductors and wiring. But those passive components don't behave as expected under all circumstances. In this article, George takes a deep look at the way these components behave with respect to their operating frequency.

COLUMNS

By
George Novacek

To draw schematic diagrams, we use common component symbols, not always realizing that passive components do not behave as expected under all circumstances. Their electrical characteristics change when the operating frequency increases. Therefore, when we design circuits, we can treat those components as ideal within a limited frequency range only.

No passive component is ideal. Passives such as resistors, capacitors, inductors and wiring combine the three fundamental electrical characteristics: resistance, capacitance and inductance. For this reason, when selecting parts, we must consider how their characteristics fit the intended design. We have to make sure their parasitic characteristics could be considered negligible within the design's operating frequency. And if they're not, they have to be compensated in some way.

Our topic is the behavior of passive components with respect to their operating frequency only. At this time, we shall not be considering other design constraints such as the operating voltage, power dissipation, magnetic characteristics and so forth. In this article, I have not considered transformers. Transformers are passive components too, but I discussed them in some detail in the *Circuit Cellar* issues 302, 303 and 304 (September, October and November 2015) [1].

Determining values of parasitic characteristics is not always easy, as few manufacturers publish them. You could measure them or, with luck, you might be able to find some data on the Internet. Some catalogs state the maximum recommended operating frequency.

Let us begin our investigation by taking a closer look at an ordinary resistor. **Figure 1** shows its actual schematic. The total resistance is the sum of the resistive element R plus the resistance of both leads R_{lead}. R_{lead} is usually a negligible fraction of R and could be ignored. Both leads also introduce a serial parasitic inductance and a parallel parasitic capacitance to the circuit. The frequency response of the impedance of two typical through-hole resistors is plotted in **Figure 2**.

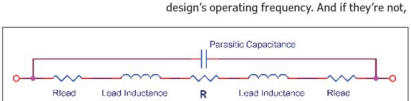


FIGURE 1
Hidden schematic of a non-ideal resistor

PARASITIC VALUES

Prevailing parasitic values of these through-hole resistors are 8 nH for the lead inductance and 0.3 pF for the capacitance. Figure 2 shows that the resistors' impedances remain essentially constant up to about 10 MHz. As the frequency increases, the larger, 50 kΩ resistor (red trace) begins to behave like an RC network with the corner frequency f=1/RC. Consequently, large value resistors are not suitable for high frequency circuits. Their frequency response can be somewhat improved by cutting the leads as short as possible or, better yet, by using SMD (surface-mount device) chip resistors.

Small value resistors, such as the 50 Ω one shown by the blue trace in Figure 2, become dominated by their parasitic inductance. This is especially true for wire-wound resistors, which are totally useless for applications at high frequencies. In radio frequency (RF) engineering, 50 Ω resistance happens to be considered a common yardstick. For the selection of other resistor values we can use the rule of thumb:

$$\frac{f[Hz]}{3\times10^{10}} \le \frac{R}{50\Omega} \le \frac{3\times10^{10}}{f[Hz]}$$

where f is the operating frequency and R is the resistance in ohms.

Just like the resistors, capacitors must also be viewed as a combination of a dominating capacitance with parasitic inductance and resistance. This is illustrated in **Figure 3**.

It is apparent that a simple capacitor is a combination of parasitic inductance of the leads L_{LEAD} with lead resistance R_{LEAD} in series connecting to the capacitance C. We must also consider two parasitic resistances R_{DC} and R_{AC}, which shunt the capacitance and alter the component's performance. **Figure 4** is the frequency response plot of the impedance of a typical 0.1 µF capacitor.

Due to its parasitic inductance of about 25 × 10^{-12} H (25 pH), the graph in Figure 4 shows, there is a series resonance around 100 MHz. At that frequency the capacitor's impedance reaches minimum.

Because the dielectric material is not an ideal insulator, R_{DC} represents the dielectric leakage, that is a DC current flowing through the dielectric material. In solid capacitors such as, for example the ceramic ones, R_{DC} is very large, reaching hundreds of megohms. But the leakage may become a significant factor with electrolytic and super capacitors where it can be in the order of microamps. R_{AC} stands for the dielectric frictional loss. The loss is due to the polarization of the charge when an AC current flowing through the capacitor changes its polarity. In applications with low

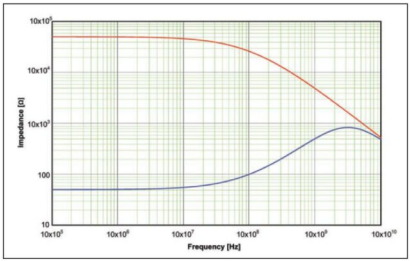


FIGURE 2
Typical frequency response of a 50 kΩ (red trace) and a 50 Ω (blue trace) resistor

FIGURE 3
Hidden schematic of a non-ideal capacitor

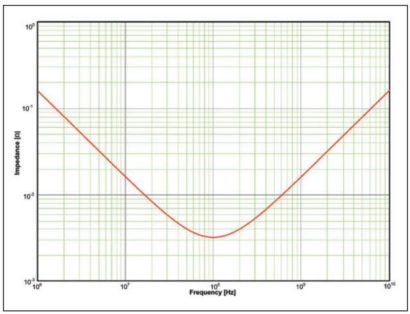
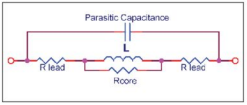


FIGURE 4
Impedance of a capacitor with respect to the frequency

FIGURE 5
Real inductor L schematic diagram



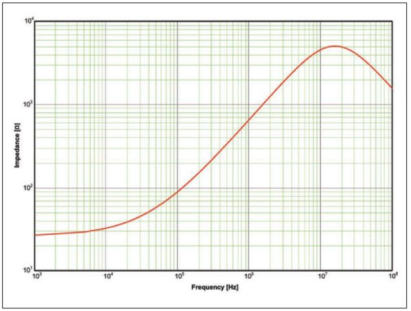


FIGURE 6
Inductor L impedance versus frequency

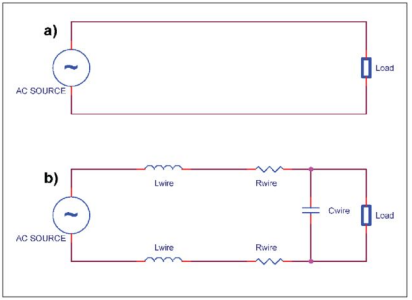


FIGURE 7
Simple wiring of a load to an AC power source (a) and its real diagram (b)

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R_{AC} the current may be excessive, causing the capacitor to heat up.

This eventuality must be taken into account when a low R_{AC} capacitor is employed in high power AC or RF applications. In component specifications, those two resistances are often combined and referred to as Equivalent Series Resistance (ESR). This is an important characteristic for applications using electrolytic capacitors. Ceramic, polystyrene and other solid capacitors are generally too small for such applications and their ESRs too small to be of a serious concern. Generally, the lower the ESR, the better. By and large tantalum capacitors have lower ESR than aluminum electrolytic ones. This is something to keep in mind especially when working with switching power supplies.

The real inductor's schematic shown in **Figure 5** is analogous to the real capacitor. In their ideal form, both capacitors and inductors are purely reactive components.

Once again, we have to account for the lead resistance R_{lead} and the parasitic capacitance. And more important, we must not forget the effects of the PCB traces. Using a chip inductor does help, but it is not a complete solution because we can't eliminate the resistance of the PCB traces. The parasitic capacitance C causes losses and the LC combination will cause parallel resonance at some frequency.

Figure 6 is an impedance plot of a 1 mH inductor exposed to a frequency sweep. Its parasitic capacitance of 0.1 pF causes parallel resonance at about 16 MHz. Inductors with a ferromagnetic core possess limited frequency response when compared with air inductors. R_{CORE} in Figure 5 expresses the core losses. Those losses are due to the non-linear hysteresis and eddy currents. They increase with frequency and are difficult to calculate.

All inductors are limited by the magnitude of the current they can carry. This limitation is brought about by the resistance of the wire from which they are wound and the size of their leads. In addition, inductors with a ferromagnetic core can handle only a certain maximum current before their core becomes saturated, which completely changes their characteristics.

WIRING BEHAVIOR

Wiring is similarly affected by hidden parasitic characteristics. **Figure 7a** shows a regular wiring diagram, while **Figure 7b** illustrates how the wiring behaves in the real world. If the wire run is shorter than about one eighth of the wavelength λ of the signal it carries and the wires are not running in parallel or not in close proximity to each other, capacitance C_{WIRE} can be omitted. The load characteristics are not considered in this

diagram, but they do interact with the wiring too.

If the conductors run in parallel, such as in lamp cords, coaxial cables, twin leads and so on, the parasitic capacitance C_{WIRE} between them may have to be considered, depending on the frequency they carry. Should the lead lengths exceed λ/8 of the signal, the wiring will have to be regarded as a transmission line. This usually is not a concern for most household wiring, where the majority of signals are of low frequency.

Power distribution wiring in homes and buildings is unlikely to behave as a transmission line because the wavelength λ of the 60 Hz mains is approximately 5,000 km (3,107 miles) or 6,000 km (3,728 miles) for 50 Hz nets. One eighth of the wavelength is then 625 km (388 miles) for 60 Hz and 750 km (466 miles) for 50 Hz. However, the situation is different for external power transmission. If we were to consider 20 kHz to be the highest frequency of an audio signal feeding speakers, its wavelength λ will be about 15 km (9.3 miles) and taking one eighth of λ, the critical lengths for the speaker wires will be 1.9 km (1.2 miles).

Most computer interfaces act as transmission lines. With the typical interface cable length between 1 m and 2 m (around 3' to 6') the critical frequencies for the transmission line behavior would be about 37 MHz and 18.5 MHz respectively. That's why longer computer cables are usually more expensive and harder to get. At higher frequencies, PCBs suffer from the same parasitic effects as any other type of wiring. However, this would be a topic of its own. Next month we'll take a closer look at transmission lines.

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George Novacek is a retired president of an aerospace company. He is a professional engineer with degrees in Automation and Cybernetics. George's dissertation project was a design of a portable ECG (electrocardiograph) with wireless interface. He's been contributing articles to *Circuit Cellar* since 1999. Contact him at gjnovacek@nexicom.net with "Circuit Cellar" in the subject line.

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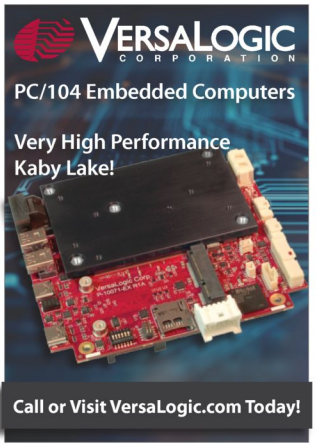
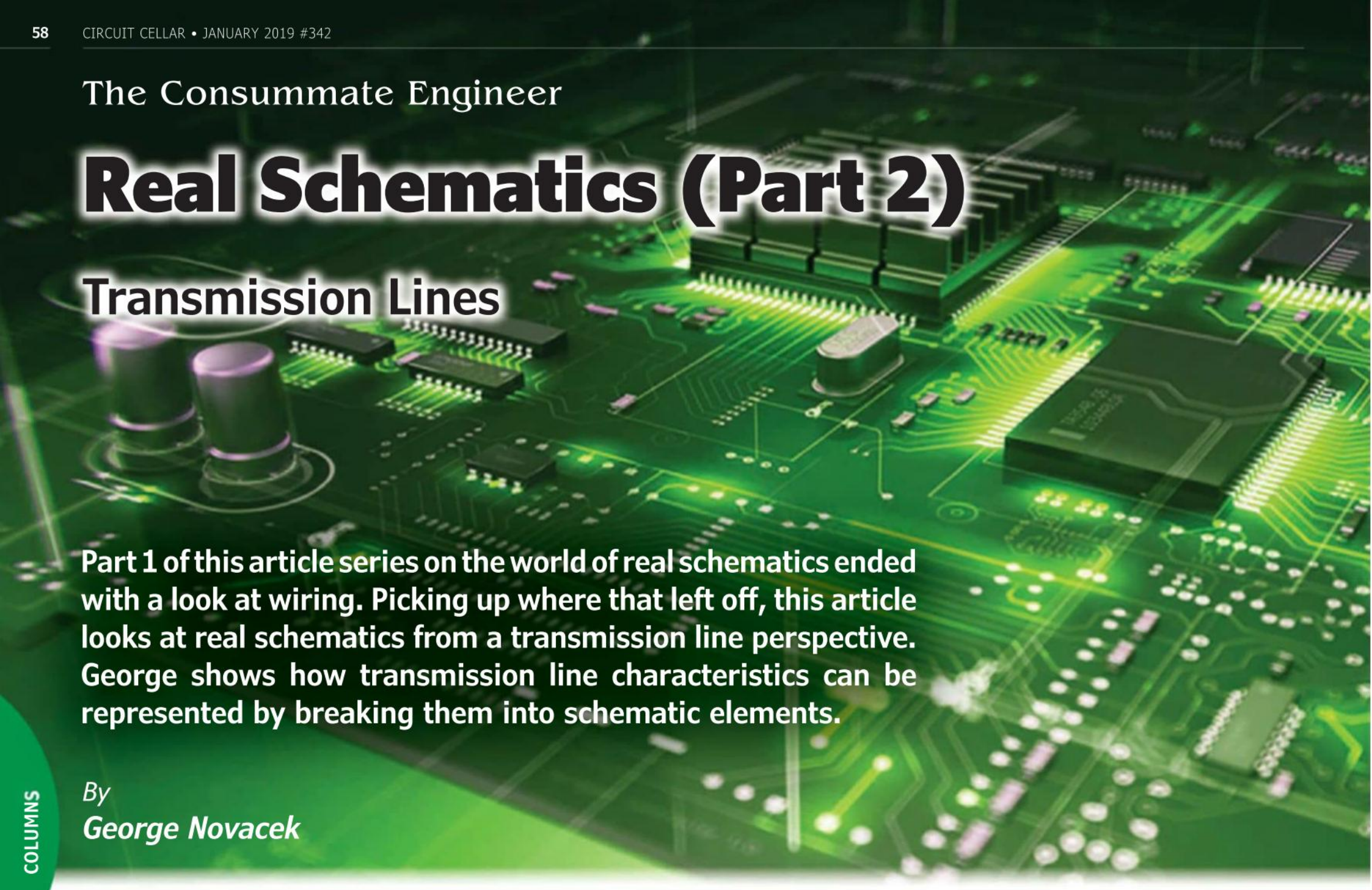


The Consummate Engineer

Real Schematics (Part 2)

Transmission Lines



Part 1 of this article series on the world of real schematics ended with a look at wiring. Picking up where that left off, this article looks at real schematics from a transmission line perspective. George shows how transmission line characteristics can be represented by breaking them into schematic elements.

By
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Our excursion into the world of real schematics ended last month (December, *Circuit Cellar* 341) with wiring. We saw that as long as an AC source connects to a load by conductors shorter than one eighth of the source's signal wavelength λ, the schematic diagram **Figure 1a** with lumped component values is a fair rendering of the circuit. The source wavelength λ in meters is approximately c/f where c is the speed of light in meters/second and f is the signal's frequency in Hertz. The speed of light is slightly less than 300×10^6 meters/second—or 299.792458×10^6 m/s to be precise. In engineering and many sciences 300×10^6 m/s is considered a good approximation.

All around us you can see power cords, coaxial TV and computer cables, twin leads, telephone wires and many other wired interfaces. Once their length comes close to one-eighth of the shortest wavelength they carry, they begin to take on transmission line characteristics. A schematic rendering of such a circuit is shown by **Figure 1b**. Keep in mind, though, that λ/8 is an empirical value at which the transmission line aspects could begin to be observed. It's not a precise wavelength at which the circuit characteristics suddenly change.

You can describe a transmission line as consisting of an infinite number of infinitesimal resistors, inductors and capacitors spread along its entire length as depicted by Figure 1b. Letter G stands for conductance, which is the reciprocal of resistance or 1/R. The unit of conductance is Siemens expressed by symbols S, Ω^{-1}, ℧ or the now obsolete "mho."

The sum of resistances R in Figure 1b represents the serial resistance of the conductor and the sum of Gs the leakage between the conductors. Because most transmission lines are made of quality materials, the resistance and conductance elements are usually negligible with respect to the circuit characteristics. It is customary to call such transmission lines lossless and ignore the resistive elements as is illustrated by **Figure 1c**. Because its elements are infinitely small, the cable characteristics are specified by their sums per one meter of length.

BUCKET BRIGADE

Figure 2, albeit simplified, explains the principle of a transmission line operation. You can compare a transmission line to a bucket brigade. Just follow along with Figure 2. Initially, when the switch SW is open (Figure 2a), there is no voltage along the line and across the load. Closing the switch connects a 5 VDC source to the line and capacitor C1 begins to charge through inductor L1 up to the source voltage level (Figure 2b). During this process some energy is stored in L1, some begins to trickle to C2 and if the switch SW remains closed, the second element L2-C2 begins to charge (Figure

2c). This is followed by L3-C3 and so forth until the wave reaches the load (Figure 2d). Because during the charging process no current flows through the load, the impedance loading the source is determined by the values of the inductance and capacitance only. This constitutes the characteristic impedance of the transmission line:

$$Z_0 = \sqrt{\frac{L}{C}}$$

From the above quation you can see that the characteristic impedance of a transmission line is purely resistive. In case we needed to consider the line losses, that equation can be expanded by adding Rs and Gs:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

where ω is the angular frequency equal to 2πf, and f is the frequency.

The characteristic impedance of the majority of transmission lines, for example coaxial cables is 50 Ω. This somewhat arbitrary value has been chosen based on several observations. First, as shown in Part 1 of this article series, a large resistance is susceptible to the parasitic capacitance, while a low resistance is mainly affected by its parasitic inductance. What we want, therefore, is a characteristic impedance to be somewhere in between, such that filters, amplifiers and other components can be reasonably sized and built.

Coincidentally, a coaxial cable with air dielectric designed for maximum power transfer happens to have the characteristic impedance of 30 Ω. An air dielectric coax designed for the minimum loss has its characteristic impedance 77 Ω, so the 50 Ω

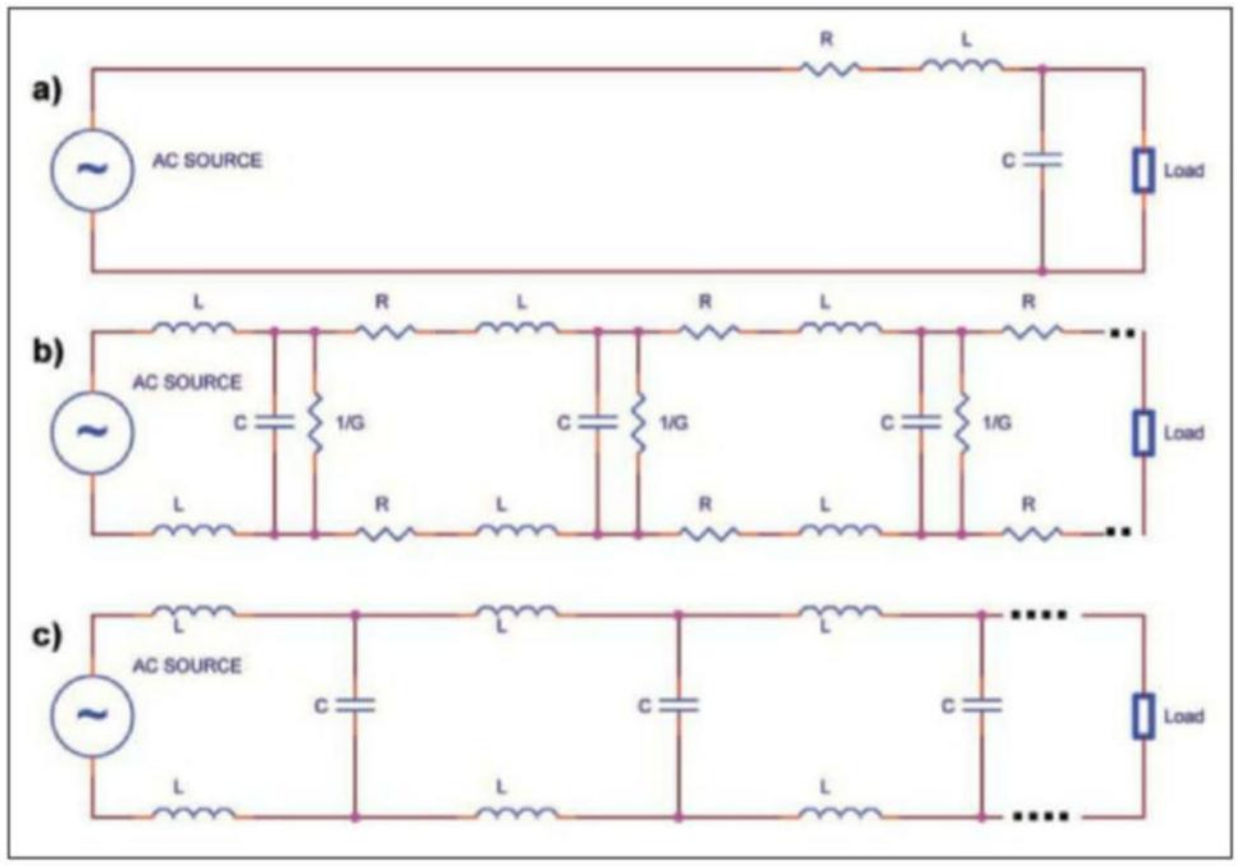

FIGURE 1
The derivation of a transmission line

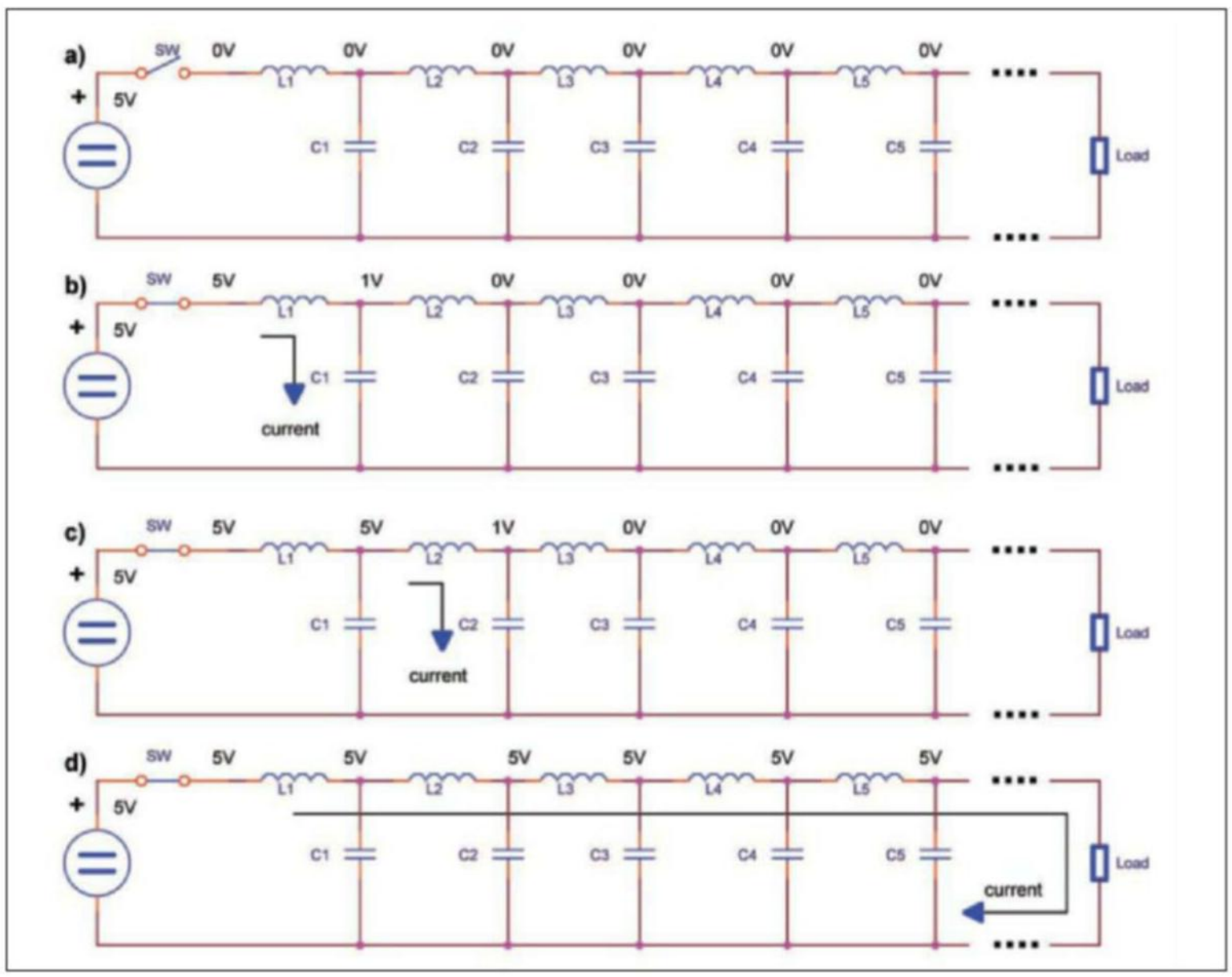

FIGURE 2
Workings of a transmission line

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cable impedance is a good compromise. Furthermore, a coaxial cable with a Teflon dielectric optimized for the least loss has 50 Ω characteristic impedance and the impedance of a monopole antenna is 50 Ω too. Cables with 75 Ω impedance and air dielectric are manufactured for applications where losses must be minimized due to long cable runs—such as for cable TV distribution.

You can also describe the transmission line by a waveguide model. The electromagnetic wave moving through a transmission medium comprises a magnetic field related to the wave current and an electric field related to the wave voltage. The wave travels through the medium at velocity v close to the speed of light, reduced by the medium's permittivity ε and permeability μ. Consequently, the wave velocity is:

$$v = \sqrt{\frac{1}{\varepsilon\mu}}$$

and the two models are related such that we can write:

$$Z_0 = \sqrt{\frac{L}{C}} \text{ and } v = \sqrt{\frac{1}{LC}}$$

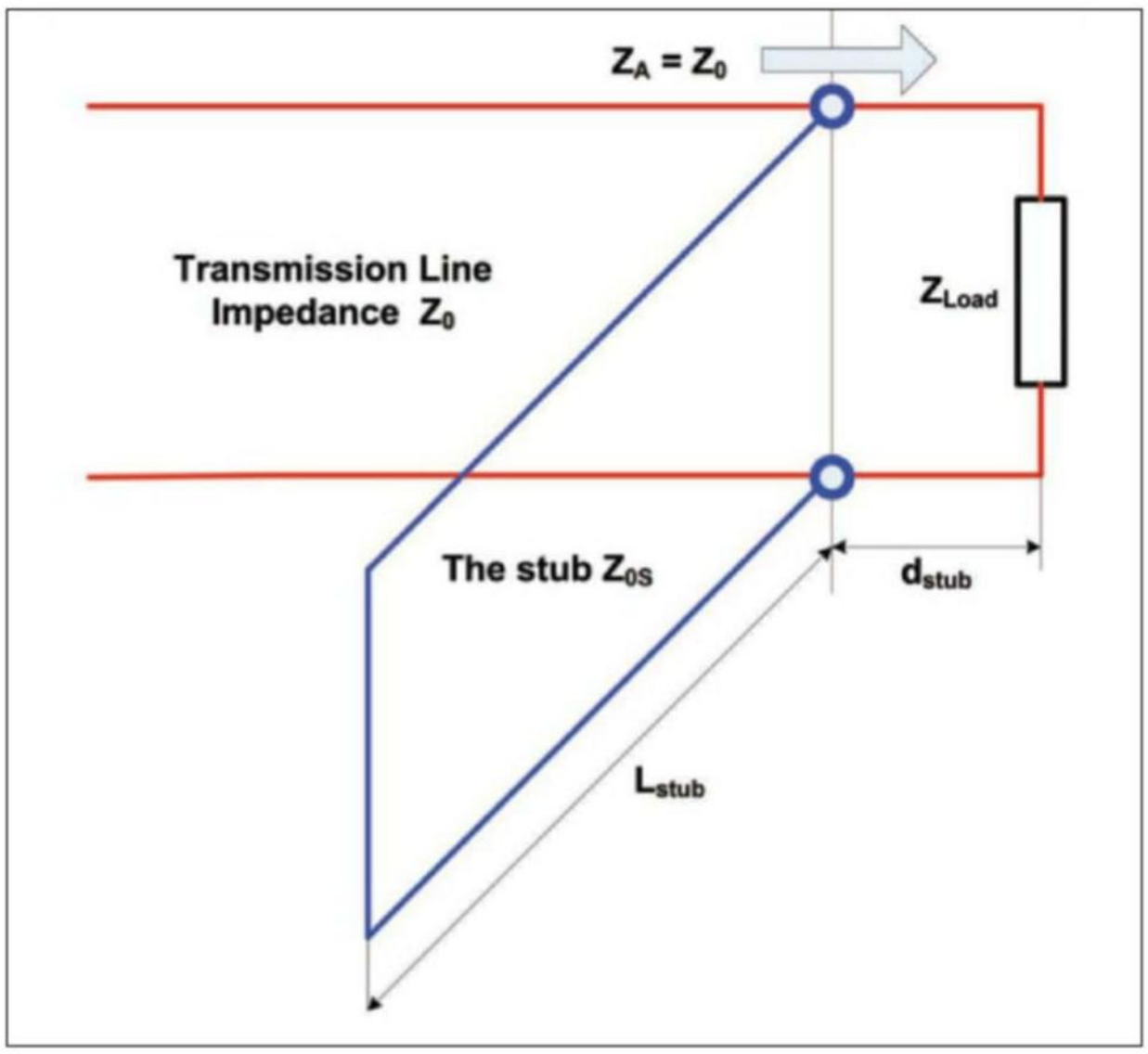

FIGURE 3
Impedance matching using a stub (blue)

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In cables where the wire pairs are separated—for example by Teflon—the wave travels at roughly 70% of the speed of light in vacuum. The equation above shows that signal propagation within a wire transmission line is slower than through vacuum, determined by the transmission line's velocity factor v. For instance, Cat-5e cable's velocity factor v = 64%. An electromagnetic wave traveling in vacuum needs 3.34 ns to travel one meter, but it takes 5.21 ns for it to go the same distance in Cat-5e cable. In other words, 1 m of Cat 5e cable delays a signal by 1.88 ns. This phenomenon is employed in signal processing for constructing delay lines. At very high frequencies transmission lines are often replaced by waveguides due to their significantly lower loss, typically around 0.2%. Waveguides, essentially metal pipes using air dielectric, are another topic.

When a traveling electromagnetic wave is confronted by an abrupt change in impedance, a part of its energy continues on its way, while the remainder is reflected back to the source. That's why impedance matching is so important for RF power transfer. The origins of power transmission physics date back to 1840, when Moritz von Jacobi postulated that maximum power transfer from a source to a load is obtained when their impedances match. But even if maximum power transfer is not your concern, the incidental and reflected waves combine, creating standing waves that can and often do destroy the signal integrity. The degree of impedance matching is expressed by Standing Wave Ratio (SWR), calculated as:

$$SWR = \frac{Z_L}{Z_0} \text{ for } Z_L \geq Z_0$$

or

$$SWR = \frac{Z_0}{Z_L} \text{ for } Z_L \leq Z_0$$

Achieving SWR = 1 is perfect, but SWR less than 2 is still considered good match. Voltage Standing Wave Ratio (VSWR) is frequently used instead of SWR because it is easier to measure. High SWR means that the reflected energy turns into heat which must be dissipated by the cable.

STUBS AND BALUNS

Stubs are fractions of transmission lines used for impedance transformation, matching and as resonant circuits. A λ/4 long stub, shorted at its output has high impedance input. Conversely, the input impedance is low when the λ/4 stub is open-ended. A λ/2 stub works the other way

around. Consequently, a stub impedance depends on its length. This phenomenon is the basis for construction of baluns—devices for matching impedances of *bal*anced with *un*balanced transmission lines [1] among other uses. **Figure 3** illustrates how a stub can be used to match impedance of a load to the impedance of a transmission line.

This technique is useful, for example, for matching a RF amplifier output to an antenna. You calculate the stub length L_{stub} and its location d_{stub} based on the frequency, source impedance and the load characteristics. But those calculations are outside the scope of this article. Transmission lines called microstrips are created on PCBs. They behave just as wire transmission lines but their design requires special skills.

All transmission lines, when properly terminated by their characteristic impedance, appear as infinitely long, no matter what their actual length might be. This applies to cables as well as PCB traces. High frequency digital signals with short rise time—clocks included—have bandwidth often extending into high Gigahertz. Just a few centimeters of a PCB trace can become a transmission line. To protect data integrity, it is imperative that such traces are properly terminated. Moreover, remember that signals on a PCB trace propagate at a speed of about 150 mm/ns (6″/ns)! This delay must be considered during the PCB layout when several signals are required to arrive at the same time.

In this two-part series, we discussed the behavior of passive components when exposed to alternating voltages and currents. The *Circuit Cellar* article materials webpage provides other sources for those interested in finer details. Next month we'll take a closer look at infrared sensors.

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George Novacek is a retired president of an aerospace company. He is a professional engineer with degrees in Automation and Cybernetics. George's dissertation project was a design of a portable ECG (electrocardiograph) with wireless interface. He's been contributing articles to *Circuit Cellar* since 1999. Contact him at gjnovacek@nexicom.net with "Circuit Cellar"in the subject line.

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